Incorporating AEGIS autonomous science into Mars Science Laboratory rover mission operations

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The AEGIS (Autonomous Exploration for Gathering Increased Science) intelligent targeting software system has been in use on the Mars Science Laboratory (MSL) mission since 2016. The system allows on-board autonomous selection of targets for the ChemCam remote geochemistry instrument based on analysis of images taken by the rover. This paper describes the deployment of AEGIS to MSL and the operational use of the system since rollout to science operations in May of 2016.

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I. Nomenclature

AEGIS	=	Autonomous Exploration for Gathering Increased Science
ChemCam	=	Remote-sensing science instrument on the MSL mission, short for 'Chemistry and Camera'
FIMOC	=	French Instruments Mars Operations Centre
FOV	=	field of view
GUI	=	graphical user interface
LIBS	=	Laser-Induced Breakdown Spectrometer
MSL	=	Mars Science Laboratory
MSLICE	=	Mission operations planning software used on MSL, the 'MSL InterfaCE'
Navcam	=	Navigation Camera
RCE	=	Rover Compute Element
RLR	=	Common type of ChemCam observation, for 'RMI-LIBS-RMI'
RMI	=	Remote Micro-Imager
RSM	=	Remote Sensing Mast
VSTB	=	Vehicle System Test Bed

II. Introduction

The Mars Science Laboratory (MSL) mission has been exploring Mars' Gale Crater since August 2012, studying sedimentary rocks in the crater floor deposits and the lower reaches of the crater's 5-km high central mound, Aeolis Mons (known informally as Mt Sharp) [1]. The rover is operated by a team on Earth, will activities planned in batches of one to several sols (Martian solar days) at a time [2]. For remote-sensing instruments on the rover, observations of specific objects in the rover's environment, called 'targeted science activities', require a ground-in-the-loop cycle for planning: images, typically from the rover's navigation cameras (Navcams) are acquired and sent to Earth, and operators on the ground select and localize targets, then prepare and uplink commands for the rover's instruments to observe them.

The AEGIS (Autonomous Exploration for Gathering Increased Science) intelligent targeting software system [3] was developed to allow on-board decision-making to select targets for remote-sensing instruments. On MSL, this is realized in two modes. In the first, called autonomous target selection, the rover chooses its targets independently, using guidance about the visual properties of desirable targets. Autonomous target selection is typically used for 'post-drive' science observations – when the rover has driven to a new location but and Earth-in-the-loop cycle has not yet occurred to allow ground-targeted science. This allows observations at the rover's new location to begin immediately after arrival, avoiding a delay of hours to days for images to be sent to Earth and activity planning to take place.

In the second mode, called autonomous pointing refinement, the rover points its instruments at targets selected by operators on Earth, but will refine that pointing automatically to correct for small errors in targeting. Some targets, such as small veins in rocks, may be only a few millimeters wide, and subtend angles of less than 1 milliradian as viewed by the rover. Even small errors of a few mrad in stereo localization could lead to missing such small targets, which necessitate a second Earth-in-the-loop cycle to correct the error on a second attempt. For such targets, AEGIS can avoid the risk of having to make a second attempt.

Both modes are used to target the ChemCam science instrument, a combination Laser-Induced Breakdown Spectrometer (LIBS) and Remote Micro-Imager (RMI) [4] [5], mounted on an articulated pan-tilt platform called the Remote Sensing Mast (RSM) . The LIBS, with a maximum range of 7 metres, is used to measure the geochemical composition of rocks and soils in the rover's vicinity. These are typically also imaged with the RMI to obtain high-resolution texture and visual information of the targets. ChemCam has become an important tool in the mission's exploration of Gale Crater [6], typically making multiple point measurements on each of several targets at each location visited by the rover. The frequent, thorough geochemical survey provided by ChemCam is an important contribution to the mission's work of understanding the history of Gale Crater, and by extension of Mars.

The use of AEGIS has given new options for acquiring ChemCam data, and increased the rate of data return from the instrument by measuring additional targets and making use of time previously unavailable for targeted observations. AEGIS-targeted ChemCam observations are an example of *science autonomy*, where a spacecraft makes decisions about which science data to gather or to transmit to Earth, and distinct from, for example, autonomous navigation, or housekeeping of onboard systems.

III. AEGIS Intelligent Targeting

AEGIS intelligent targeting begins with acquisition of the 'source image' with an onboard camera; for autonomous target selection, the rover's stereo Navcams are used, while autonomous pointing refinement uses RMI images. The system then uses a computer vision algorithm to identify and segregate geological features as potential targets. In the MSL implementation, this target-finding layer is an algorithm called Rockster [7], which segments features using a technique best on detection and grouping of edge segments in the grayscale source image. With a number of targets found, AEGIS can then filter and rank them based on a variety of computer vision features derived from pixel values of the area contained within the boundaries of each target. These can include, for example, average grayscale pixel brightness, total area in pixels, size or distance from ChemCam (estimated from Navcam stereogrammetry). Linear combinations of these features can be selected for target ranking. The combination of selection target-finding parameters in Rockster and adjusting target filtering and ranking settings allow the definition of 'scene profiles' corresponding to finding particular types of targets in a given range of visual settings. One commonly-used profile on MSL, for example, finds light-toned patches of rock outcrop among sand, soil, and loose rock; another finds bright veins in darker surrounding host rock.

Once the source image has been taken and AEGIS has found, filtered, and ranked targets in it, follow-up observations with ChemCam can begin. During activity planning on Earth, operators choose these settings for these observations – the number of targets to observe, the type of ChemCam observation(s) to make on each target, and other instrument operations and data management parameters. AEGIS will initiate the ChemCam follow-up observations immediately after completing target ranking, without any Earth-in-the-loop step. The full process of AEGIS intelligent targeting is elaborated in [3].

IV. Safety Considerations for ChemCam

All activities planned for the rover are subject to a number of checks, constraints, and flight rules to ensure the safety of the rover and the payload. In the case of ChemCam, the nature of the instrument necessitates two particular safety considerations for all observations. First, the instrument focuses its laser, spectrometer, and the RMI through a 110-mm diameter Schmidt-Cassegrain reflecting telescope to achieve observations at a range of distances [6]. This telescope can also focus light from external sources into the instrument, producing a risk of damage to sensitive hardware if ChemCam is pointed at the sun. As such, *sun-safety* concerns preclude pointing ChemCam too near the sun, and, for assurance, near the path the sun will take through the sky. Even targets on the ground can be precluded by sun-safety constraints, if for example they are not sufficiently below the horizon as viewed from the rover's mast, where ChemCam is mounted.

The second concern particular to ChemCam operations regards the safety of the rover itself. ChemCam LIBS observations employ a powerful laser, able to deliver over 1 GW/cm^2 to the target, which is sufficient to turn (a small part of a) rock into glowing plasma visible to the ChemCam spectrometer [4]. For this reason, it is important that ChemCam LIBS observations are not made of any part of the rover hardware (with the exception of the ChemCam calibration targets carried on-board). This requirement is termed *collision safety*, in that the laser beam should never be in collision with rover hardware.

For conventional targeted science observations with Earth in the loop, operators validate each ChemCam observation for sun-safety and collision, using ground tools which model the position of the target(s) and the rover hardware as viewed by ChemCam. For autonomous targeting activities, the precise position of the targets is not known to the operators at uplink time – this introduced a need for new procedures to validate autonomously-targeted observations.

AEGIS can only choose targets which are visible in the source image field of view (FOV). In the case of autonomous pointing refinement with an RMI source image, the FOV is relatively small – only 19 mrad in diameter – meaning that the final target will be very close, in angular space, to the original pointing selected. For these cases, it is therefore possible to validate collision- and sun-safety in a similar way to conventional human-targeted observations. While ordinarily operators must only validate safety of the original target, when employing autonomous pointing refinement, they must validate safety of the full RMI FOV around the original target, since the final target selected by AEGIS may be anywhere in that region.

This approach is not practical for autonomous target selection activities using Navcam source images. The MSL Navcams have a 45-degree square FOV, making the area extremely large for target validation. More importantly, however, these activities occur post-drive, when the rover is at a different location than it was a planning time – very often a location which has never been seen before. This means that the position of the targets with respect to the rover and the sun is not fully known at planning time (indeed, it's not even known which targets AEGIS will select, or which it will have to select from). The problem cannot be solved by pre-analysis of the post-drive location, since typically there is little or no imagery available of that location before the drive, and since unexpected events can cause the rover to end a drive in an unplanned location or orientation.

For the post-drive case then, both procedural and software safeguards are necessary to ensure that, no matter which target(s) AEGIS chooses, all ChemCam follow-up observations will be sun-safe. Additionally, since the Navcams are attached to the same pan-tilt mast as ChemCam, the Navcam source image must also satisfy sun-safety pointing constraints. The solution used in routine operations is to point the Navcam source image with rover-relative azimuth and elevation angles. In this way the motion of the mast as it slews to the source image pointing is known, and the bounds of possible target positions relative to the rover is also known, since they must be within the source image FOV. By pointing the source image at very low elevation, it is possible to ensure it will be below the sun-risk area even for high rover tilt at the end of the drive (another variable which is not fully predictable at planning time). Typically the Navcam source image is pointed at a rover-relative elevation of -47 degrees (that is, 47 degrees below horizontal). This keeps the pointing sun-safe for all tilt values seen so far in the mission, and also means that for most rover attitudes, the terrain in the FOV is at distances where ChemCam can focus and measure them with LIBS.

The sun-safety of the ChemCam follow-up activities is made likely by this low-elevation pointing, since any targets seen in the source image will typically be well below the horizon. To fully ensure sun-safety of the follow-ups even for unexpected tilts and orientations, AEGIS incorporates on-board checks for the ChemCam observations. Since the position and path of the sun through the sky are known and predictable, non-sun-safe areas in their vicinity can be excluded by rule. Included in each AEGIS activity are defined "sun-safety keep-in boxes" – rectangular areas in azimuth/elevation space which are known to be sun-safe. After acquiring the source image and finding targets, the target list is filtered so that targets inside a defined sun-safety keep-in box are retained. Current practice is to define sun-safety keep-in boxes valid for 100-day increments, avoiding the need to define and validate them daily. A planned upgrade to ground tools would replace these 'seasonal' sun-safety boxes with daily automatic generation of suitable boxes. An example of how mission operators visualize the sun-safety of post-drive activities is shown in Figure 1.

For collision safety, AEGIS incorporates a model of the rover hardware and excludes from consideration any targets which are on the rover or near it in angular space. The model includes articulated elements such as the rover chassis, high-gain antenna, and robotic arm, to account for unexpected positions of any of these, or their intrusion into the source image FOV.

These procedures and on-board checks are designed to minimize the complexity of planning faced by ChemCam and MSL operations personnel. For the autonomous pointing refinement case, the procedure for sun- and collision safety is the same as for full ground-targeted observation, except that the checks extend to the 19-mrad diameter area surrounding the target, rather than only the target itself. For post-drive autonomous target selection, the on-board collision check, sun-safety keep-in filter, and a standard set of known-safe Navcam source image pointings mean that post-drive AEGIS-targeted observations require far less planning effort than ground-targeted observations.

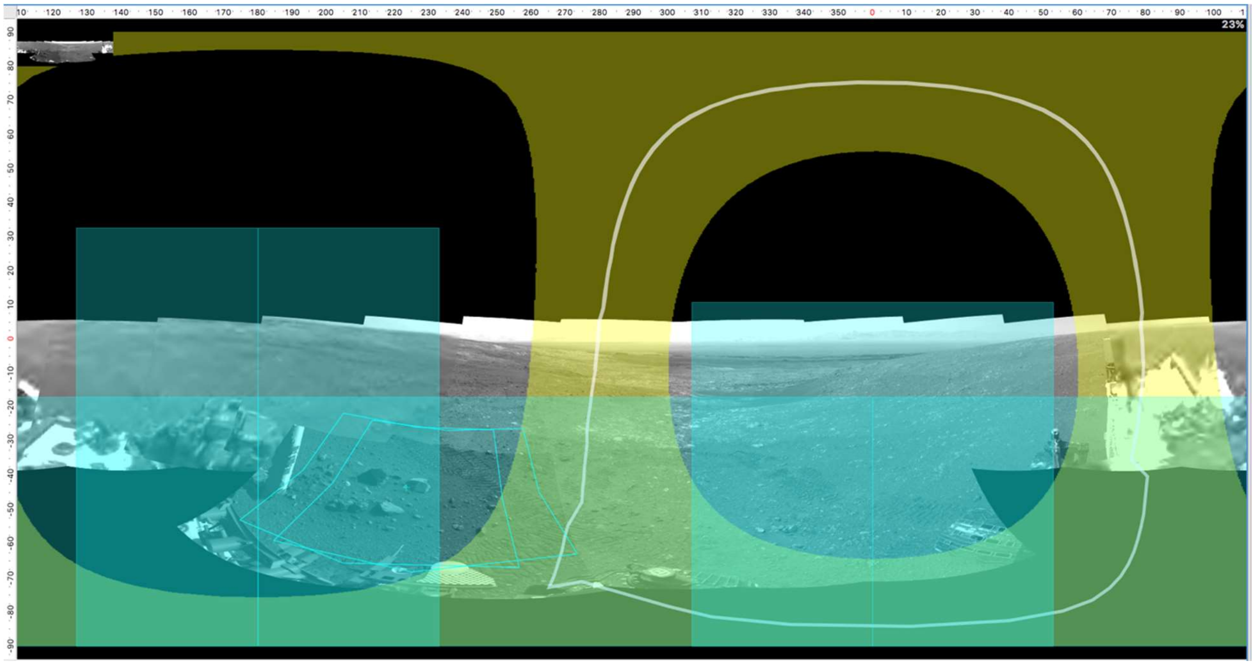

Figure 1 - Sun-Safety planning view for post-drive ChemCam activities. This view is available to mission operations personnel using the MSLICE planning software. The Navcam mosaic at the rover's current location is shown, with azimuth and elevation angles, in local geographic co-ordinates. The path of the sun through the sky over a particular day is visible, as well as the yellow sun-safety zone around it. The sun-safety keep-in boxes are shaded in blue – AEGIS will only select targets which are inside at least one of these boxes. Two overlapping polygons to the left of centre represent the FOV of the Navcam stereo source image. Because that image will be taken after the rover drives away, its position with respect to the sun path and sun-safety boxes is not known (due to uncertainty in the rover's post-drive tilt and heading). For the same reason, the rocks and terrain visible in the Navcam mosaic will are not those which will be visible from the rover at the time of the AEGIS activity – the rover will have driven to a new, yet unseen locale.

V. Deployment and Checkouts

The AEGIS system deployed to MSL is an evolution of the system used for autonomous targeting of the Pancam instrument on the Mars Exploration Rover *Opportunity* [9]. The system was adapted to the MSL flight computer, hardware, and software environment, with additional considerations added for targeting ChemCam, such as the safety requirements discussed in section IV, and the need to compute accurate stereo range to the targets to focus ChemCam on them.

The MSL version of AEGIS underwent a thorough ground testing program in 2015, with testing on the MSL mission's software simulators, and on the full-rover hardware simulator, the Vehicle System Test Bed (VSTB). These tests were designed to demonstrate the full function of the system. This included checking that it ran correctly under all modes and options, and that it successfully identified targets and repointed the mast to make ChemCam observations, as well as validating the onboard checks for collision and sun safety. The tests also verified the use of AEGIS during typical operational scenarios, when the MSL flight computer has a number of tasks to manage at once. Verifying that AEGIS could safely be run in parallel with other key rover activities was an essential step in ensuring its feasibility for use in operations, and the ease and flexibility of its use on the mission.

Following the successful ground test series, the AEGIS system was approved for uplink to the flight-model *Curiosity* rover on Mars in September 2015. This was followed shortly by installation into the rover's flight software, in October 2016. The program then proceeded to flight model checkouts. The AEGIS software checkout program demonstrated the system's safe and effective operation on Mars through a staged series of progressively more complex activities.

Each of the two modes – autonomous pointing refinement and autonomous target selection – was exercised in a three-part process. In the first part, the software is activated, the source image is acquired, AEGIS analyses it to find targets, the target filtering (including the safety checks) and ranking is carried out, and co-ordinate frames for targeting are placed at the locations of several top targets; this process is repeated for several source images. Following a ground-in-the-loop cycle for assessment of the results, the second part of the checkout repeats these steps, but continues with pointing ChemCam at each of the targets and acquiring RMI images. For each selected target, the software commanded a series of motions replicating the pointing used for an entire ChemCam LIBS raster, and acquired an RMI image at each position of the raster. This practice allowed verification that AEGIS-guided ChemCam targeting and pointing behaved as expected, and that the aiming of ChemCam at the targets was accurate and as desired. Confirmation of this by analysis on the ground resulted in clearance for the system to fire the ChemCam laser for the first time; in the third part of the checkout, the system repeated again the intelligent targeting process, finishing with full ChemCam LIBS observations on several selected targets, along with RMI images before and afterward. This RMI-LIBS-RMI ('RLR') raster approach is the typical measurement practice for ChemCam in science operations, and demonstrated fully that AEGIS was able to make scientific measurements of the same kind previously only commanded by the team on Earth. Analysis of the resulting RMI and LIBS data by members of the ChemCam team confirmed that the images and spectra were in focus and of the same quality as ground-targeted observations.

Six checkout activities were needed to run this three-part test on each of the two intelligent targeting modes. A seventh activity, completed last, demonstrated a combined mode in which AEGIS autonomously selects an outcrop target from a Navcam source image, obtains an RMI image of that target, then runs autonomous pointing refinement to recentre its pointing, cued to centre on light-toned veins in the outcrop.

The full seven-part process took place during the period from November 2015 to January 2016 (mission sols 1157 to 1237). Each of the seven checkout activities required significant time and onboard resources, given that it was making observations on several targets, and as such these activities had to be accommodated in the schedule of the ongoing MSL science mission. In particular, this period included nearly a month of tightly-scheduled activities to study the Bagnold dune field [10], which had been planned in detail for over a year. AEGIS checkouts were scheduled around the dune campaign, as well as routine science activities and operations stand-downs for holidays in November and December 2015.

With completion of the final step and a positive assessment of the downlinked results, AEGIS was qualified for ChemCam operations on the MSL flight mission in February of 2016.

VI. Initial Rollout to the Science Team

The AEGIS checkouts were followed by a program of training and preparation for the introduction of the system into regular use in operations by the mission Science Team. Personnel responsible for ChemCam instrument operations and MSL mission operations were trained in the basics of the AEGIS system, and details of the autonomous-targeting operations appropriate to their roles. The entire mission science team was provided with an introduction to the system and its capabilities, to allow them to understand the role it would play in the mission, and how they might be able to use it as part of their investigations.

Autonomous targeting was a new type of operation for the mission, and it required operators to adapt to a different practice of sharing responsibility for decision-making with the robotic system, and of validating activities. AEGIS can be operated in two different modes, each with a number of parameters and options, and together with a complex instrument in ChemCam offers a significant new range of possibilities. To ease the transition into routine use of autonomous targeted science, he decision was made to conduct a staged rollout of the capability. The initial rollout would include a simplified capability in each of the two AEGIS targeting modes. For autonomous pointing refinement, a single scene profile (for light-toned veins in rocks) was deployed, with a single type of ChemCam observation (an RLR measurement with a 3x3 grid of LIBS points); the team could use this observation on any target in the rover's workspace which was suitable for ChemCam. For autonomous target selection, again a single profile was available (for light-toned rock outcrop), with the Navcam source image pointed at a rover-relative azimuth of 90 degrees (to the right of the rover) and elevation of -47 degrees, and the follow-up measurements were also set to a consistent 3x3 RLR. For further caution and to avoid confusion between the two modes, the ChemCam team agreed to use the autonomous targeting mode first, and complete downlink assessment and review, before making use of the autonomous pointing refinement capability.

Prior to rollout, it was necessary to update ground tools used in mission planning, especially the MSLICE operations planning software system [11], to represent the available AEGIS activities. Checklists for validating AEGIS activities were developed, and mission and ChemCam checklists were also updated. With these steps and the team training completed, AEGIS was released for Science Team use in May of 2016.

The MSL Science Team first made use of AEGIS on mission sol 1343, and as desired, it correctly selected a patch of outcrop and measured it with ChemCam. This initial success soon led to regular use, especially of the post-drive capability. The initial scene profile, having been developed with images of earlier terrain, was adapted with the experience of the first few weeks of runs on Mars, and a new version of the Navcam outcrop profile was uplinked, and first used on sol 1400. This update also introduced a second version of the post-drive activity, in which the rover would conduct ChemCam measurements on two targets, instead of only one. The team would thereafter select whether to use AEGIS post-drive, and whether to measure one target or two, during the planning of each drive sol.

These three standard activities (RMI pointing refinement with fixed settings, and post-drive one- and two-target autonomous targeting) would remain in use, with periodic updates to the sun-safety keep-in boxes, while the team became accustomed to using AEGIS autonomy in planning, and while the mission prepared updates to procedures and ground tools to support the full rollout of the system.

VII. Full Rollout: Upgraded Flexibility

The initial rollout allowed the mission operations teams time and experience using AEGIS as part of regular operations, and to become comfortable with the autonomous targeting and confident in the system's performance at selecting suitable targets. The team also developed strategies for using the system as part of the mission's exploration work (described below in section VIII). The limited number of activities, however, led to certain constraints – for example, while ChemCam activities can be adjusted for shorter duration when time is constrained in a plan, all of the parameters on the AEGIS activities were fixed.

The second stage of the AEGIS deployment, termed the 'full rollout' addressed this restriction, and also made available all of the options and parameters for AEGIS intelligent targeting, and for the ChemCam activities on AEGIS-selected targets. No upgrade to the flight software was needed – the initial installation in October 2015 had been full version of AEGIS – but extensions to the ground tools and additional team training allowed the full range of AEGIS' on-board capabilities to be used for the first time. Most notably, these enhacements included fully-adjustable representations of the all AEGIS activities and the ChemCam follow-up activities in the MSLICE planning software, and a series of *command expansion* scripts which transform the activities represented in the MSLICE graphical user interface (GUI) into sequences of commands for the spacecraft, to be uplinked to the rover.

Three key enhancements became available to operators with the AEGIS full rollout in December 2017. First, the teams could now select the pointing of the Navcam source image for autonomous target selection. Second, the parameters of the ChemCam activities were now adjustable, including the shape of the raster, number of points and number of laser shots per point, focus settings, etc., as well as the number of targets. Importantly, these parameters were adjustable during planning, to allow for changes during the development and refinement of the plans over the course of the planning day. Finally, the full rollout also allowed for the definition of new scene profiles, to adapt to new terrain into which the rover was soon expected to drive, or simply to choose different types of geological materials.

The new activities remain in routine use, with more varied AEGIS and ChemCam activities now in play than before, and new strategies evolving from their availability.

VIII. Use in Operations

AEGIS activities are part of the Science Team's array of tools for science and exploration; as with the others, it is used strategically and tactically when it can provide data and insight to advance the MSL mission's science objectives. In each planning cycle, the tactical operations team selects activities for the plan which meet the goals for that cycle, informed by the rover's current context and guidance from strategic and supra-tactical planning [2]. The building of plans is accomplished using the MSLICE planning software, which includes a GUI having representations of possible activities for the rover and its payload. Figure 2 shows a view of the MSLICE planning GUI, with a simplified activity plan for a typical drive sol. AEGIS activities are typically accommodated within the *science blocks*, marked in blue. These are periods set aside for observations with the rover's science instruments, and have two basic forms: a *targeted* science block occurs before any drive in the plan, so that the rover's position at the time of the block corresponds to the most recent stereo images of the rover's environment available to the operations team. Post-drive science blocks, also called *untargeted* blocks, will occur with the rover in a different location. As such different types of observations can be planned in the post-drive blocks – only those which do not require ground-in-the-loop targeting information.

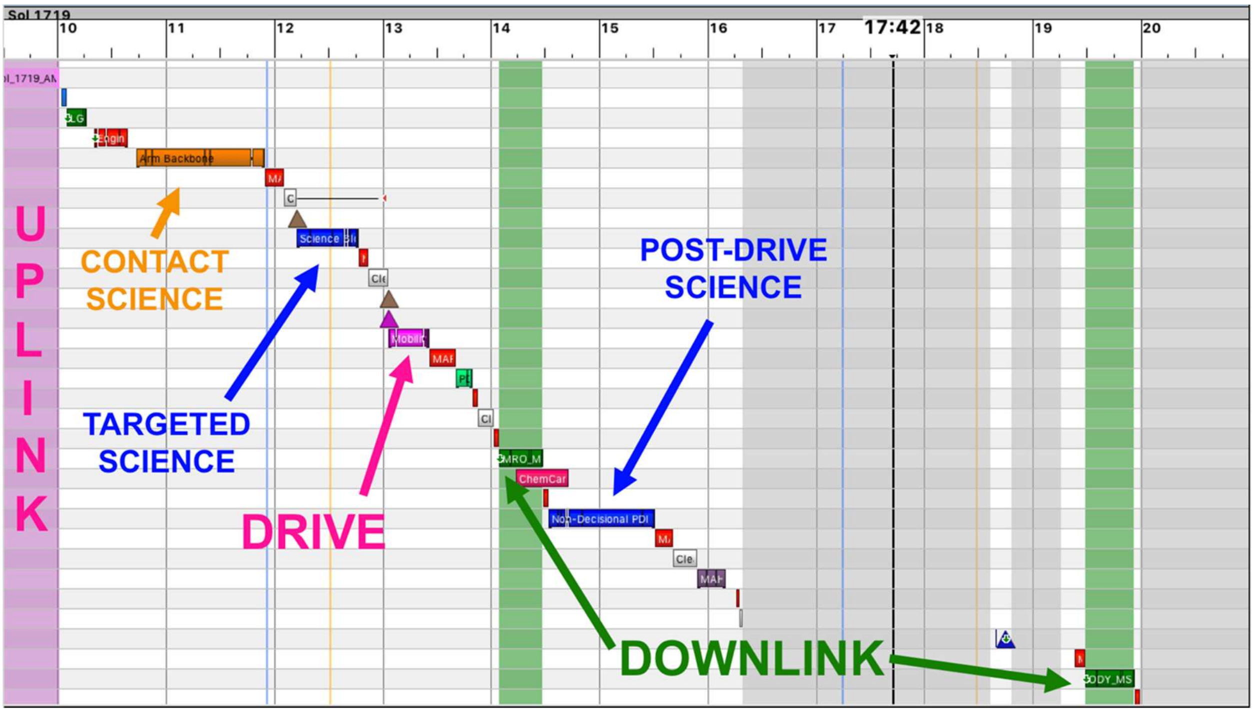

Figure 2 - MSLICE GUI Planning view. This simplified example of a mission plan as viewed in MSLICE shows a typical sol with a drive. Pre-drive activities include contact science using instruments on the rover's robotic arm, and a targeted science block for observations with mast-mounted instruments. Another science block is available post-drive.

Typically, autonomous target selection activities are included in post-drive blocks, while observations which make use of the autonomous pointing refinement occur in the targeted science blocks. In either case, the activities are typically drawn from a set of *activity templates* defined for AEGIS activities. Shown in Figure 3, these include the range of commonly-used activities, and alternate options.

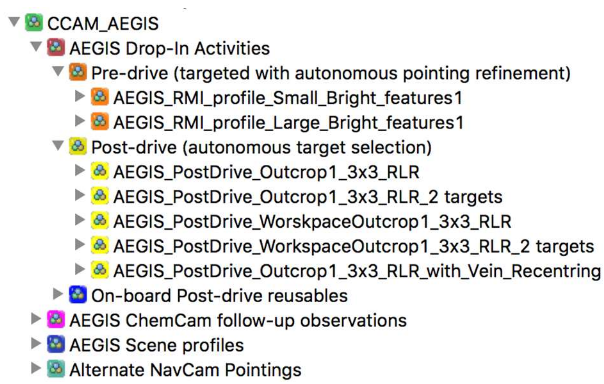

Figure 3 - AEGIS activity templates. A view of AEGIS activities defined in MSLICE for MSL science operations

Based on the experience from the initial rollout, the templates include a set of 'drop-in activities' which require no adjustment by the team – this allows AEGIS activities to be planned with minimal effort and without adding to the complexity of plans. These templates are, however, adjustable during planning – operators can change AEGIS parameters (such as the source image pointing, number of targets to measure, and scene profile to use) and the parameters of the ChemCam follow-up observations. A common adjustment is to reduce the usual 3x3 RLR observation to a 5x1 RLR, saving several minutes' duration. When time or onboard resources constrain the duration of the post-drive science block, this reduced duration can sometimes allow an AEGIS activity to fit.

Autonomous pointing refinement activities are typically included when small targets, usually veins, present a challenge to measure on the first attempt. They do come with the cost of several minutes of plan time which is modeled for AEGIS to acquire and process the source image. Given the high value of time in targeted science blocks, the team will often elect to instead measure a similar, but larger target (if such an alternate is available) and use those minutes for another observation. While AEGIS typically completes RMI image acquisition in under two minutes, and processing and target selection in 90-120 seconds (for a total of 3-4 minutes), planning carries several minutes of margin to account for the possibility of a longer duration, since the time taken to process the image depends on the scene content. For the pointing refinement case, 3 targets have been observed since AEGIS rollout in May 2016, and in all cases AEGIS correctly adjusted the pointing to achieve a measurement of the desired feature. The less frequent use of this mode is attributable both to the premium placed on time in targeted science blocks, and to the fact that the rover has spent much of its time since the AEGIS rollout in areas where small, difficult-to-target veins unaccompanied by larger, more readily targeted and related features, were relatively infrequent.

Post-drive autonomous target selection also involves a few minutes of processing time, which varies with the complexity of the scene and is approximately linear in number of targets found (Figure 4). But the scheduling of post-drive activities is often more flexible, since they do not need to be completed in before the communications pass which will deliver critical data to Earth for the next planning cycle. Multi-sol plans, especially where the drive is not on the final sol of the plan, also allow flexibility of resource management; data and power budgets can sometimes be traded between sols, which can further favour inclusion of extensive post-drive science activities.

Since the Science Team began using AEGIS on sol 1343, the majority of plans which included a drive also included post-drive AEGIS autonomous target selection with one or more ChemCam follow-up observations. This is particularly the case in multi-sol plans; AEGIS has been used in 63% of multi-sol plans with drives. Not including AEGIS post-drive is typically because it isn't possible – if energy-intensive activities are scheduled in the same plan, for example, the science block time may need to be reduced to the point that AEGIS-targeted ChemCam observations can't be accommodated. This frequent use has led to observation of 138 AEGIS-selected post-drive targets by ChemCam, as of this writing. Notably, AEGIS has performed extremely well in selecting patches of rock outcrop in post-drive autonomous target selection; consistently well above 90% of the targets selected turn out to have all of the LIBS shots on the desired outcrop material [3].

These post-drive targets represent an increase in the number of targets measured by ChemCam, and consequently an increase in the rate of scientific data returned from the instrument. Figure 5 shows the cumulative number of ChemCam LIBS measurements since the start of the mission; the average rate has increased from 256 LIBS shots per sol before AEGIS rollout to 320 shots per sol since. These additional measurements significantly add to the density and completeness of the mission's geochemical survey along the rover's traverse; they also provide improved statistics on the bedrock measurements, which is helpful in improving a number of geological and geochemical analyses.

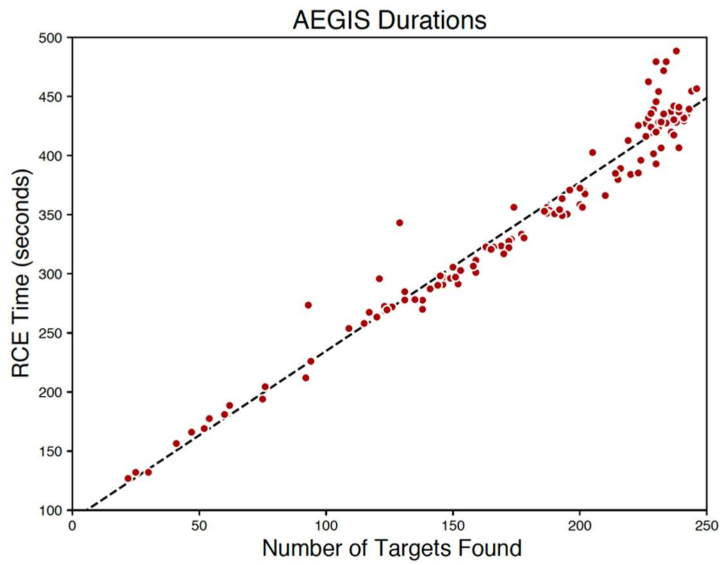

Figure 4 - Duration of the autonomous target selection process. This plot shows total duration of the process for AEGIS to find targets in a Navcam stereo source image. This includes the time to acquire the image itself, as well as process it to identify targets, extract their visual properties, and determine stereo range to each of them. The duration indicated is time spend on the task by the rover's onboard computer, the Rover Compute Element (RCE).

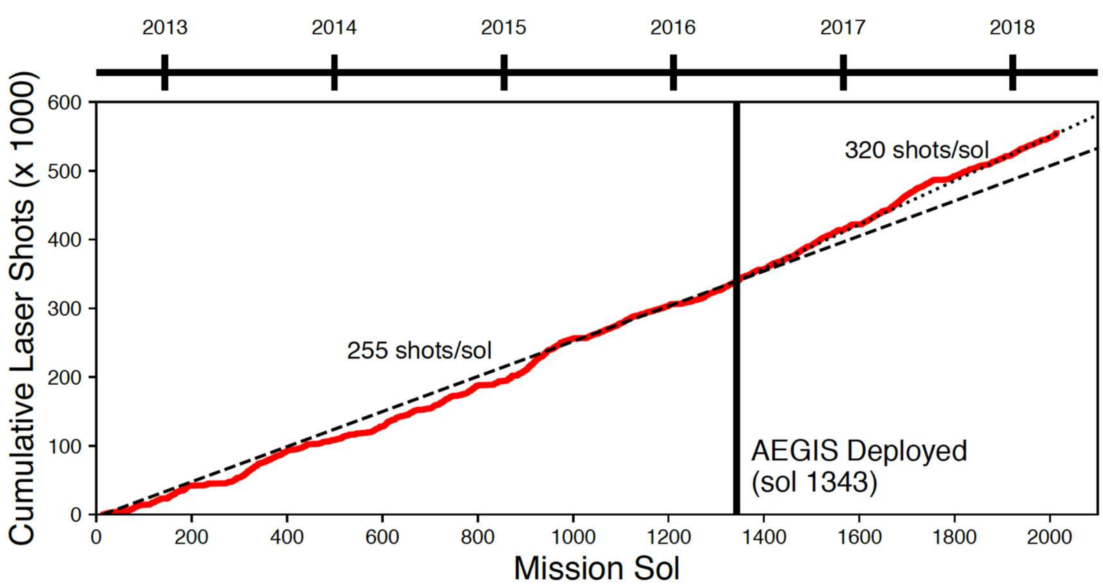

Figure 5 - Cumulative count of ChemCam LIBS shots per sol. The pace of ChemCam measurements has varied over the course of the mission – interruptions from operations stand-downs are visible, for example, where the cumulative shots curve goes horizontal for an interval. Overall, the average rate of ChemCam measurements has increased significantly since AEGIS autonomy became available.

IX. Applications and Strategies for Autonomous Science

Nearly two years of use in operations (as of this writing) have given the MSL and ChemCam operations teams significant experience with the use and utility of autonomous targeting. Autonomous pointing refinement has principally been used for its expected purpose, of assuring the success of targeted observations of very small targets. For autonomous target selection, the expected role of acquiring additional data during times not previously available for targeted ChemCam has proven to be the main application, but routine use of this capability has revealed a number of strategies and specific utilities of this kind of autonomous science.

A. Division of work between operators and the autonomous system

During the initial rollout of the AEGIS system to science operations, the post-drive autonomous target selection was restricted to a single target profile, tuned for light-toned patches of outcrop. Regular use of AEGIS meant that such outcrop observations were frequently and routinely made, with very high success rate at measuring the desired target material [3]. When the team was presented with a new workspace, it became the frequent practice to focus on observations of other materials than the local bedrock, since AEGIS had already acquired a bedrock measurement shortly after the drive. To an extent, this meant that AEGIS could be used to complete much of the survey of local bedrock, while ground-targeted observations, with the benefit of human analysis and judgement, could be used to investigate other materials – veins, distinctive clasts, suspected meteorites, unusual textures, and other notable potential targets. This role of AEGIS making bedrock measurements and freeing time to be used for other observations contributed to the studies of the first apparent ataxite meteorite measured on Mars [12] and of newly-discovered boron in hydrothermally-precipitated veins [13], among others.

This represents an example of automating part of a suite of tasks, but bringing human expertise to bear on the more diverse or unpredictable cases – a strategy which is employed in many other fields where automation has made advances.

B. Expanding capabilities with constrained time

AEGIS' measurements of local bedrock are not simply of the same material at each location along the rover's traverse; this bedrock varies along the route, and with stratigraphic elevation. In some cases several distinct geological units are visible in a given rover workspace, but constraints in the duration of targeted science block time available may preclude measuring each of them before the rover drives away. In one such case, on sol 1673, the rover's workspace included the clear exposure of three distinct materials with clear contacts between them. Rover resources only allowed for ChemCam measurements of two of the units in the targeted block, but fortunately AEGIS had selected a target in one of the three units and measured it with ChemCam shortly after the drive to that location on sol 1672.

In this case, use of the post-drive science block for autonomously-targeted observations led not only to more data, but to the opportunity to complete a survey of a geological contact of interest to the team. The only other alternative would have been to remove other observations from the sol 1673 plan, or delay the drive away at a cost of at least one sol of time on Mars and progress along the rover's traverse.

Similarly, the mission occasionally encounters periods when targeted science block time is particularly constrained, usually because energy-intensive activities are being carried out. During certain phases, only enough targeted time for a single ChemCam target is available for several sols in a row. The addition of post-drive science with AEGIS means that during these phases, the number of ChemCam targets at each location can be increased by a factor of two or more.

C. Opportunistic and serendipitous science

Making more measurements can lead to unexpected discoveries, and sometimes this is even helped by measuring automatically without humans in the loop – the autonomous system may select measurements differently than the human teams. The post-drive AEGIS target from sol 1612, for example, holds the record for highest chlorine content ever measured by ChemCam on Mars – this expansion of the range of rock chemistry is a notable discovery. In several other cases, unusual chemistry seen in the post-drive AEGIS targets has prompted the science operations team to follow up with additional ground-targeted measurements at the same or nearby locations to further study the materials seen in autonomously-selected ChemCam targets.

D. Quicker delivery of data to enhance decision-making

Depending on the timing of downlink opportunities from the rover, the locations of post-drive AEGIS targets, and even the ChemCam data from them, is sometimes delivered to the operations team in time for the next planning cycle. Where planning at the new workspace previously meant that selection of ChemCam targets could begin, in many cases use of AEGIS post-drive now means that planning at the new workspace begins with geochemical data already available, on one or more targets in the workspace. To make use of this capability, the Navcam source image for the post-drive AEGIS activity is sometimes aimed at the portion of the workspace reachable to the rover's robotic arm, allowing ChemCam data to inform the selection of targets for the arm-mounted instruments – a task that previously required an extra ground-in-the-loop cycle.

E. Working when humans can't

Several cases have shown the utility of this kind of on-board autonomy when human operators are not able to take action, for various reasons. In the sol 1979 plan, for example, constraints on downlink data volume meant that a significantly reduced set of Navcam targeting images were available for planning. Since the operations team can only select ChemCam targets they can see in the Navcam images, their effective workspace was reduced in that plan. The post-drive AEGIS activity on sol 1978, however, had had its field of view pointed in the area without downlinked targeting images – a ChemCam observation on a bedrock target was made in that area, which would otherwise have gone unseen and unmeasured.

During the preparation of the sol 1672 plan, communications difficulties on Earth interfered with the effective use of the planning tools, preventing ChemCam operators from validating targets and transmitting command sequences to the operations servers. Fortunately, the reusable AEGIS activity command sequence from the initial rollout (see section VI) was kept on board the rover, and could thus be executed without the usual ground tools for delivering sequences. As a result, the only ChemCam observations made in that plan were those on AEGIS-selected targets.

The most expansive activity yet run with AEGIS occurred during the December 2017 holiday operations stand-down. The MSL operations teams co-ordinate a holiday from operations planning for several days in late December each year; in the past, this meant that ChemCam measurements could not be made for lack of operations personnel. The rover's activities during the holiday stand-down period have typically been restricted to those that do not require target validation or significant operator planning support. In 2017, this included AEGIS-targeted ChemCam observations for the first time. Over the course of an 8-sol holiday plan, AEGIS was active on 3 sols, selecting a total of 6 targets and measuring each of them with ChemCam. Future holiday plans will likely make use of this kind of autonomous survey work.

X. Conclusion and Future Directions

AEGIS autonomous targeting for ChemCam has become a routine part of the MSL science mission, and an important tool for maximizing the mission's use of its time on Mars and its capable payload suite. More than a full Mars year – nearly two Earth years as of this writing – of regular use in MSL science operations have given the team a significant understanding of the system's capabilities and utility, and of strategies to make the most productive use of it. Importantly, AEGIS on MSL has given the team experience in sharing responsibility for science planning between the human operators on Earth, and a capable science autonomy system on Mars. This includes learning which activities to plan with humans, and which to rely on the autonomous system for, when autonomous science of this kind is most useful for planning, and for science, and how to validate the safety of activities whose precise pointing isn't known at planning time. Procedural approaches, inclusion of safety considerations in the software design, and the adoption of novel strategies have all been required to enable enhanced science from ChemCam and MSL while keeping both the instrument and the rover safe.

The AEGIS capability, and the practice of its use, will continue to evolve on MSL. The results from this mission, including its contributions to operational efficiency and especially to scientific results, have led to its inclusion in the next: AEGIS is planned to be available for NASA's Mars 2020 rover, from the beginning of the surface mission.

Beyond Mars, the kind of science autonomy demonstrated by AEGIS and practiced with ChemCam and MSL will be important, even enabling for mission to more distant destinations in the solar system. While near-daily planning is possible for Mars surface missions, orbital mechanics and the light-speed limits of radio signals mean that missions to many other planetary bodies have even less opportunity for ground-in-the-loop planning. Such missions would benefit greatly from capable autonomous science systems able to take some of the responsibility for scientific measurements in unexplored terrain, and their mission plans and science return may be greatly enhanced by the inclusion of such capabilities.

Acknowledgments

Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The AEGIS team thanks the Mars Science Laboratory and Mars Exploration Rover missions, the ChemCam instrument team and the MSL Science Team for their support during development and deployment of the system.

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